AFFDL-TR-65-88
Part II

INVESTIGATION OF STRUCTURAL SEALING PARAMETERS AND CONCEPTS FOR SPACECRAFT

PART II. LEAK DETECTION - REPAIR, GENERAL ENVIRONMENT, AND MATERIAL PROPERTIES

Anton Hehn and Frank Iwatsuki
IIT Research Institute

TECHNICAL REPORT AFFDL-TR-65-88, Part II

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Air Force Flight Dynamics Laboratory
Research and Technology Division
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio

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FOREWORD

The research summarized in this two-part report (Part I "Design Criteria," Part II "Leak Detection and Repair, General Environment, and Materials") was performed by IIT Research Institute, Chicago, Illinois, for the Applied Mechanics Branch, Structures Division, Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, under AF Contract AF 33(615)-2202. The research was concerned with the investigation of parameters for efficient sealing of pressurized spacecraft compartments and factors affecting the maintenance of efficient sealing. The Project Number is 1368, "Structural Design Concepts;" the Task Number is 136808, "Structures for Spacecraft." Frank E. Barnett of the Air Force Flight Dynamics Laboratory was the Project Engineer. The research was conducted from 4 November 1964 to 15 April 1965 by A. Hehn and F. Iwatsuki (Principal Investigators), W. Courtney, W. DeMuth, M. Glickman, C. Gustafson, and W. Jamison.

Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

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ABSTRACT

Part I: Design Criteria

Part II: Leak Detection - Repair, General Environment, and Material Properties

The many factors that influence the leakage of gases past a seal are discussed and analyzed, in Part I, to apprise the designer of pressurized spacecraft compartments of the problems of achieving and maintaining a seal when extremely low leakage rates are desired. The nature of the leakage path is described, and the ways in which leakage occurs are categorized as interstitial, interfacial, and permeation flow. Methods of predicting leakage for these flow regimes are given with greatest emphasis placed on the interfacial flow phenomenon which is characteristic of lightly loaded, demountable seals. In the experimental phase of this program, the sealing characteristics of elastomers were studied to determine relationships between contact stress and leakage with hardness as a parameter. It is concluded that the analytical techniques presented are applicable to the evaluation or design of spacecraft seals.

The information contained in Part II is related to the overall problem of producing and maintaining a satisfactory seal but not directly applicable to spacecraft seal design or evaluation. It is included to apprise the designer of the potential detrimental effects of environment on a seal. The problems of leak detection and repair are discussed and techniques that have been investigated by various organizations are directly referenced. The general and induced environments to which spacecraft may be subjected are discussed to indicate the severity and almost endless combinations of environments. A brief discussion of the properties of rubber and plastic materials is included.

CONTENTS

CONTENTS (Cont.)

FIGURES

TABLES

NOMENCLATURE

A = orifice area

C_d = discharge coefficient

P_c = cabin pressure

Q_t = volume flow rate

R = gas constant

T_c = cabin temperature

V = volume

d = orifice diameter

k = constant

m = meteoroid mass

Φ = flux

SECTION I

INTRODUCTION

This is Part II of a two part report entitled," Leak Detection - Repair, General Environment, and Material Properties." The information contained herein was not included in Part I because it could not be directly classified as seal analysis or seal design criteria, but nevertheless provides peripheral information which is useful to the spacecraft seal designer. The following subjects are covered in this report.

Leak detection and repair techniques

General characteristics of the natural and induced environment to which spacecraft may be exposed

Properties of rubber and plastic materials for seals

This information is presented primarily for the purpose of apprising the spacecr[illegible] designer of the potential hazards to a sealed spacecraft s[illegible] due to the natural and self-induced environment to which i[illegible]s exposed. However, it is cautioned that the general information which is presented must be used in proper perspective since many sealed areas will not receive direct exposure, for example, to meteoroids or solar radiation. Therefore, modifications must be made to the data in accordance with the specific spacecraft and seal design, duration of exposure, etc.

Part I discusses in more detail the problems and methods of interpreting and applying environmental and material properties data to seal evaluation and design.

SECTION II

LEAK DETECTION, LOCATION, AND REPAIR

Astronauts traveling through space confined within a sealed pressure vessel must be provided with a life-sustaining atmosphere. Many hazards exist that could cause the loss of this atmospheric environment by impairment of the pressure retaining integrity of the cabin. Therefore, it is desirable to provide means for detection of leaks and pinpointing their location as well as prevention of excessive loss of life support and pressurizing gases. Table I summarizes the subjects pertaining to these problems which are discussed in this section.

1. REQUIREMENTS FOR LEAK DETECTION AND REPAIR SYSTEMS

a. Sensitivity of Leak Detector

Every pressurized space vehicle will have a minimum leak which cannot be eliminated without imposing unreasonable size and weight penalties. Leakage occurs primarily past the demountable seals which are used for items which penetrate and break the continuity of the pressure skin such as observation ports, access doors, exit hatches, etc. Permeation of gases through materials of construction add to overall leakage rates and in most cases is small in relation to other leaks except where degradation of a material may greatly increase its permeability or when leaks past hermetic seals are being considered.

Examples of normal leak rates are the 300 STP cc/min leakage of the Mercury series capsules and the estimated 1000 cc/min at 7-psia cabin pressure of the Apollo-type vehicle. The leak detection system must respond to an increase in leakage above the normal rate. Therefore, the minimum leak rate which the system must be capable of detecting is the total normal leakage rate or a fraction thereof depending on whether a single sensor or multiple area-sensors are used.

Reference to Figure 1 gives an indication of the substantial leakage which can take place through small openings. Based on the above examples of normal leakage rates, the equivalent hole size for the minimum leaks which must be detected cover a range of 0.003- to 0.010-inch diameter.

b. Time for Detection, Location and Repair

The time available from initiation of the leak until repair may be estimated by reference to Figures 2 and 3. Figure 2 shows the mass of gas in the pressurized compartment versus the

Table I

Leak Detection and Repair

Leaks

Degradation, Seal Failure, Faulty Installation

Puncture

Fatigue Cracks, Meteor Penetration

Leak Detection

In-Flight:
- Microphone (acoustical)
- Impact detector
- Wire grid detector
- Membrane (thin film)
- Bag detector
- Sound detector (ultrasonic)
- Pneumatic fuse

In-Lab:
- Mass spectrometer
- Halogen type
- Bubble type
- Soap solution type
- Displacement type

Leak Repair

Manual Repair

Self Sealants

a. Mechanical Foams
   - Microballoons
   - Cured elastomer Sealants

b. Chemical
   - Latex swelling type
   - Two component sealant

Seal Replacement

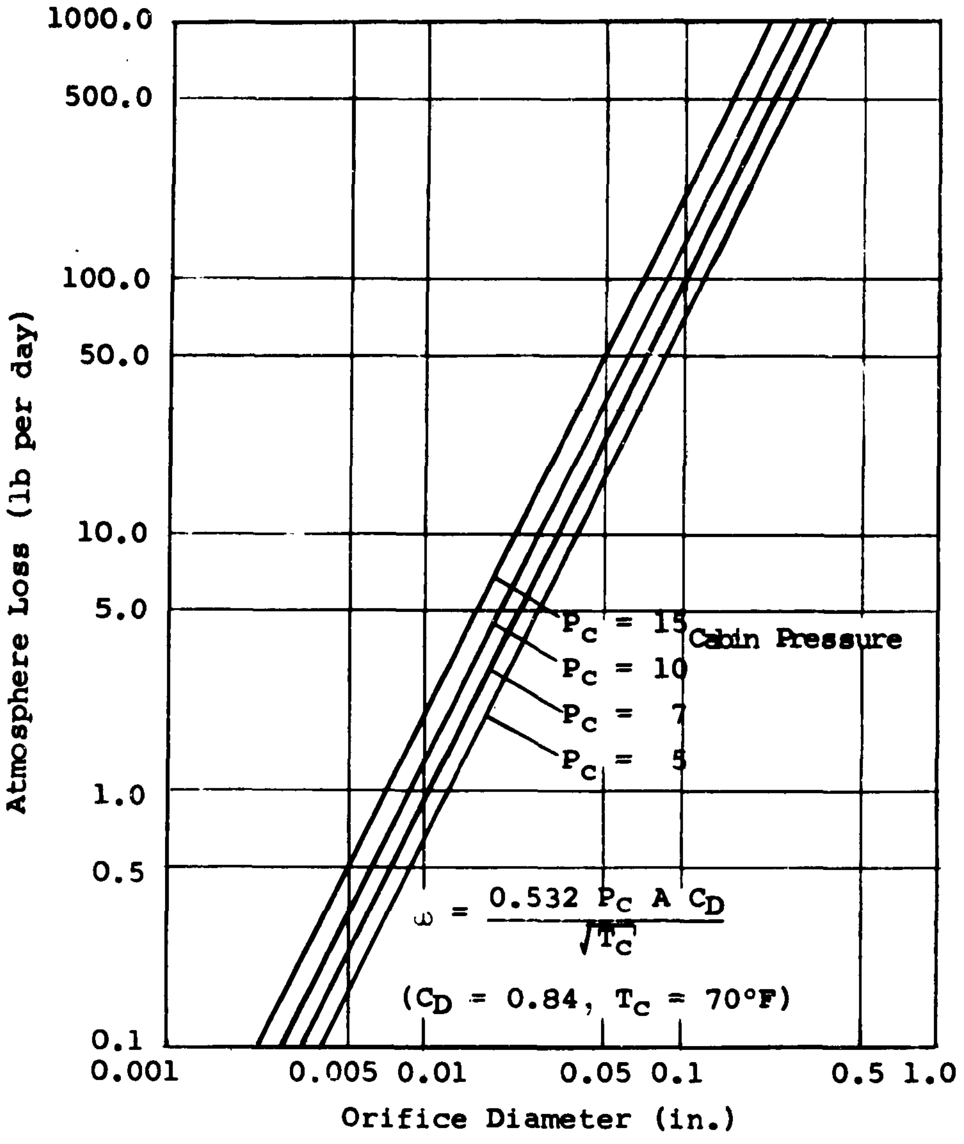


Figure 1 Cabin Atmosphere loss vs. Hole Diameter (Ref. 1)

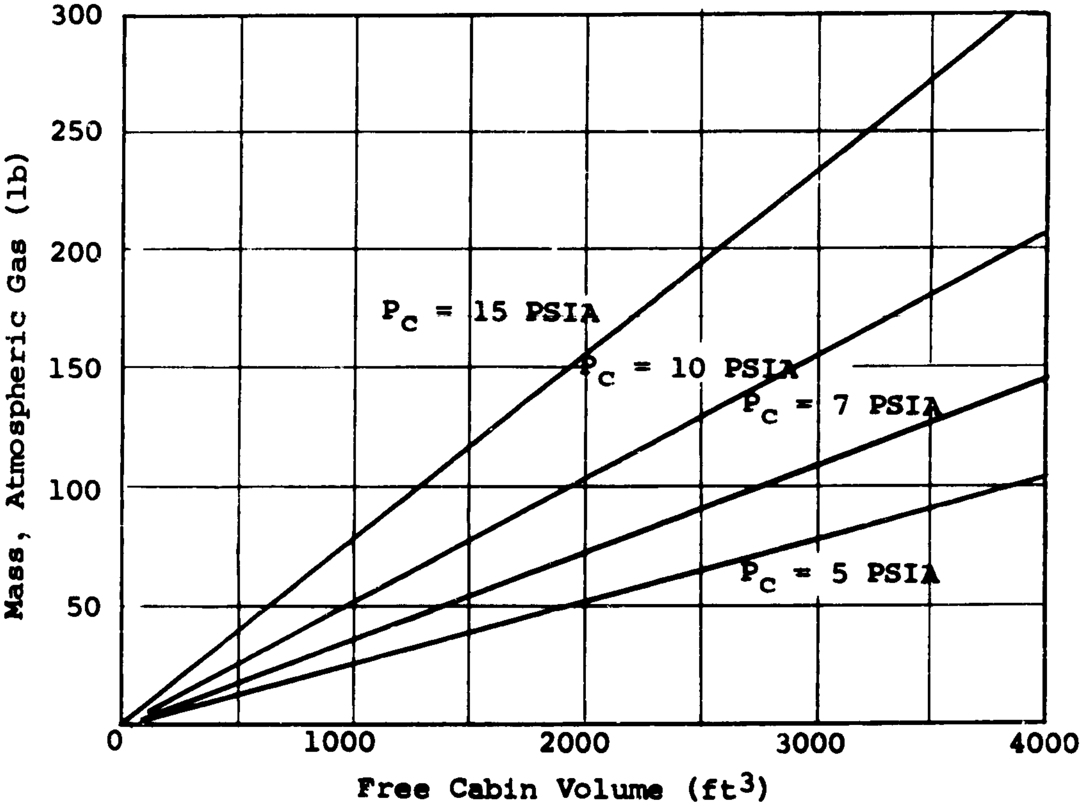


Figure 2 Mass vs. Volume for Cabin Atmosphere

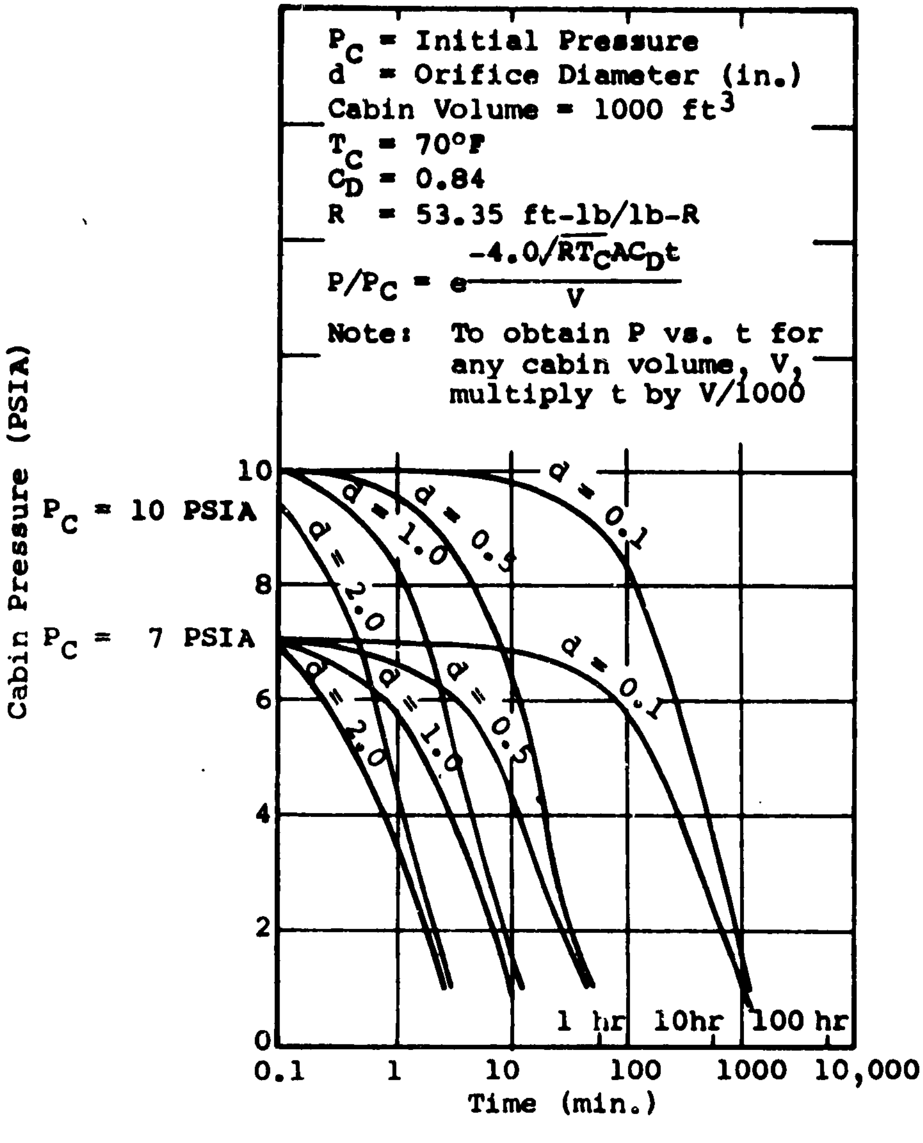


Figure 3 Pressure Decay - Standard Air Composition (Ref. 1)

cabin volume. Figure 3 shows the rate of pressure decay for different hole sizes which can be expected for a free cabin volume of 1000 cubic feet. From these figures one can see that some leaks can be repaired at the crew's convenience, others require instantaneous action, and very large leaks may cause or require decompression in which case crew safety is of primary consideration after which a relatively long period of time may be available for repair.

c. Leak Location

Leaks must be pinpointed or their general location indicated depending on the type of repair technique available. One of the difficulties in visual inspection even though holes 1/16 inch and larger are readily detectable by this method is the large amount of on-board equipment which will obscure the view and must be moved.

For all leaks which cannot be visually detected, other means for precisely pinpointing the leak must be devised or a repair technique based on treatment of the entire suspected area may be necessary, for example, a quick setting sealant sprayed or brushed over the area.

d. Warning Devices

Two types of warning devices will be necessary since the size of the leak will determine the urgency and the order in which crew functions will be carried out. A leak large enough to cause very rapid loss of pressure requires crew safety actions to be utilized whereas small leaks may only require leak location and repair. In any event the warning system should be selective, audible and visual. It must also be capable of being tested at regular intervals to insure its proper functioning.

e. Reliability of System

Since prompt detection and location and repair of abnormal leaks is necessary to assure crew safety and continuous mission operation it is obvious that the system should have a high degree of reliability. Simplicity in terms of number of components as well as minimum maintenance requirements will improve reliability, although redundant systems may be necessary.

f. Leak Repair

Size of leak and its accessibility for repair will determine the applicability and effectiveness of any particular repair technique. Therefore, it will probably be necessary to establish well defined repair procedures and perhaps instrumentations which will indicate quickly the most suitable repair technique. Variations in materials and characteristics of the leak path will influence the selection of repair methods. For extremely large leaks which endanger the structural integrity of the spacecraft, structural repair techniques such as welding and bolted or riveted patches may be required. For leakages caused by seal failure, removal and replacement of the faulty seal must be readily accomplished with minimum gas loss.

2. SUMMARY OF METHODS FOR DETECTION, LOCATION AND REPAIR OF LEAKS

a. Detection Methods

Various methods of detecting leaks have been proposed by various investigators (Ref. 1,2,3). Some of these are summarized below and more detailed descriptions can be obtained from the referenced sources. In addition to in-flight methods, laboratory leak detection and measurement techniques are described because of the potential applicability of some of these techniques to spacecraft application.

(1) In-Flight Detection Methods

(a) Pressure Decay

If the cabin atmosphere consists of oxygen and a diluent gas such as nitrogen, measurement of the pressure decay of the nitrogen after its make up supply has been closed would enable calculation of the total leak rate. Figure 4 gives a chart for calculating total leak rate from 1000 cubic foot space for a change in ΔpN_2 of 5 mm Hg. It is based upon the following equation:

$$Q_t = 56{,}632 \left(\frac{V}{t}\right) \frac{(P_o-P)}{(P_o+P)} \text{ cc/min} \qquad (1)$$

where V = cabin volume (ft^3)
t = time (min)
P_o = initial nitrogen partial pressure, pN_2
P = final nitrogen partial pressure

(b) Diluent Supply Rate

This method is based on the premise that the only loss of diluent gas in the cabin will occur through leakage. Therefore, monitoring diluent supply rate will provide an indication of overall cabin leak rates. One system suggested by General Electric (Ref. 1) is shown in Figure 5.

(c) Vacuum Gauge Detection

Various types of low pressure measuring gauges, such as ionization gauges, could be placed in the interspace between the pressure hull and heat shield to detect pressure changes or presence of air molecules caused by leakage. One such concept (Ref. 1) is shown in Figure 6.

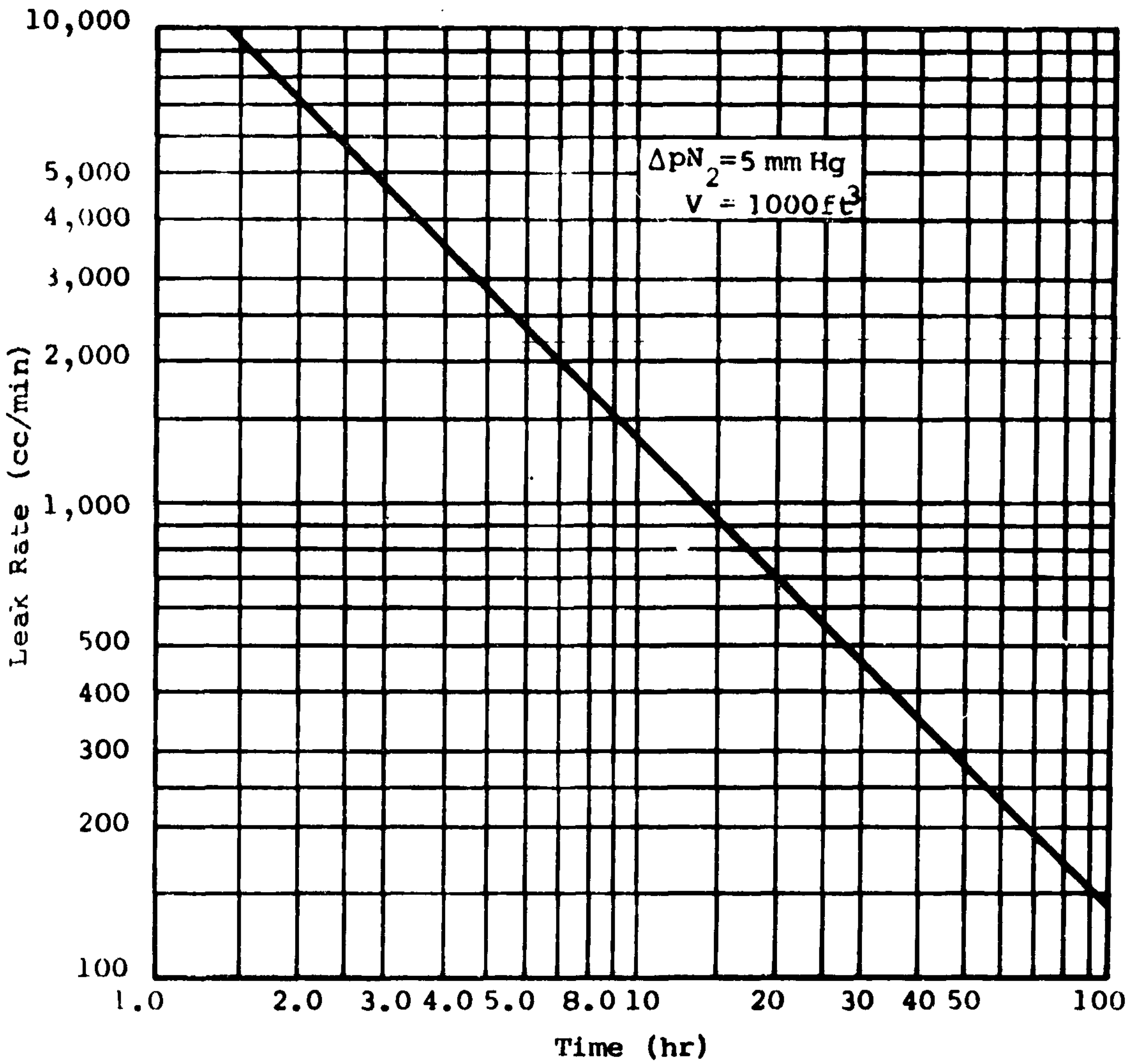


Figure 4 Total Cabin Leak Rate vs. Time

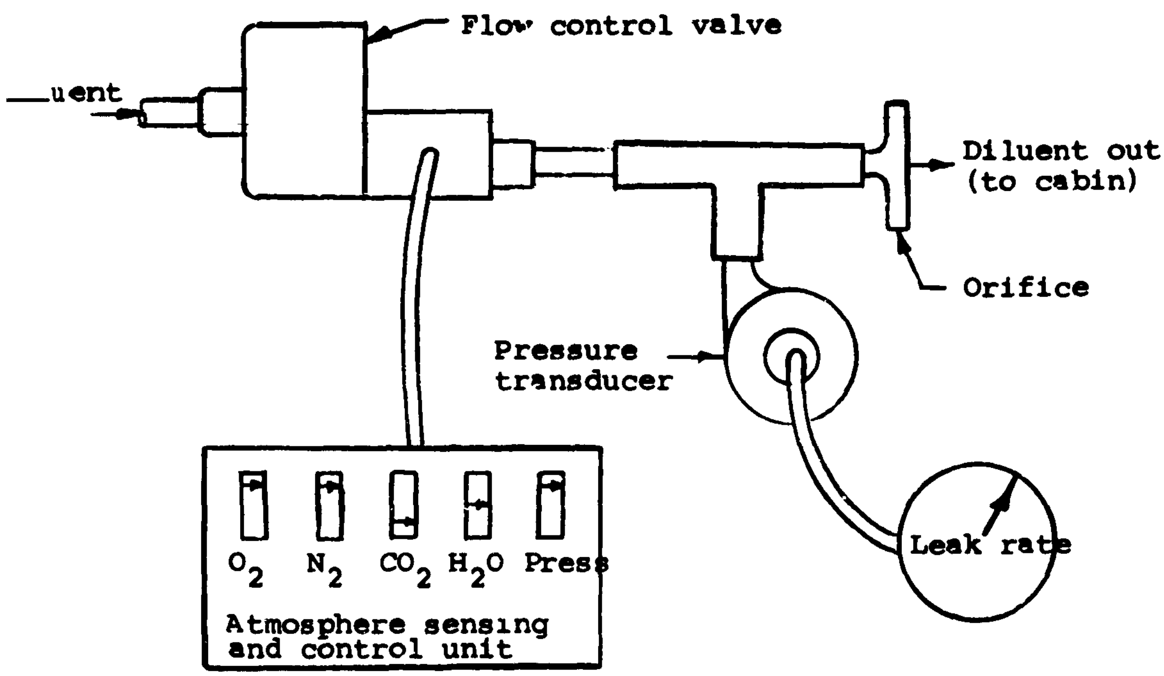


Figure 5 Continous Flow Diluent Supply
Leakage Detection System (Ref. 1)

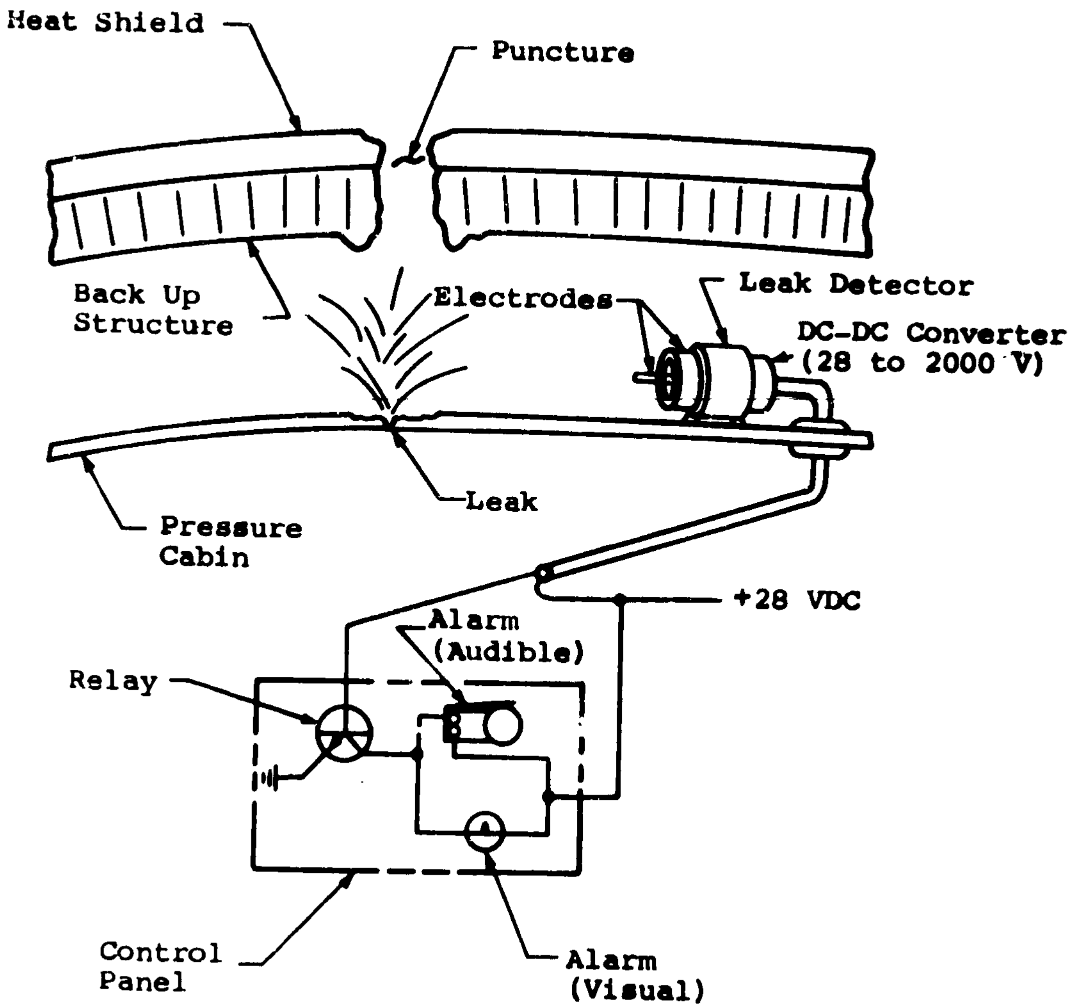
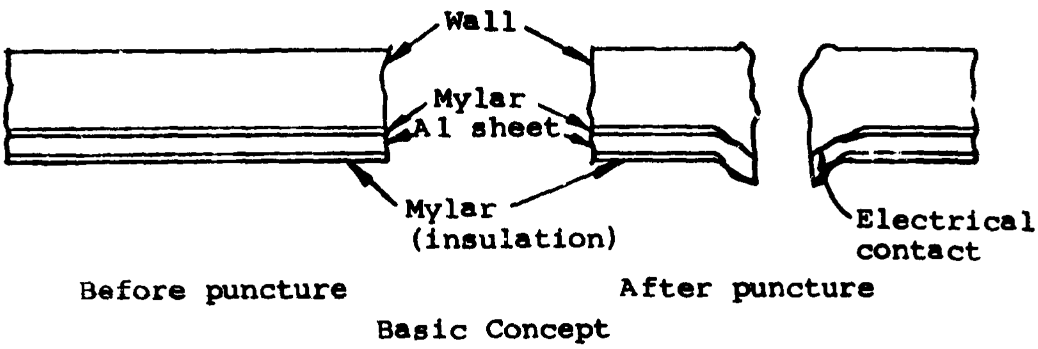


Figure 6 Basic Concept Ionization Gauge Leak Detector (Ref. 1)

(d) Discontinuity Sensor

Techniques based on an electrical conductor grid system or short circuits caused by puncture and deformation of insulated metal panels have been suggested. One method is shown schematically in Figure 7.



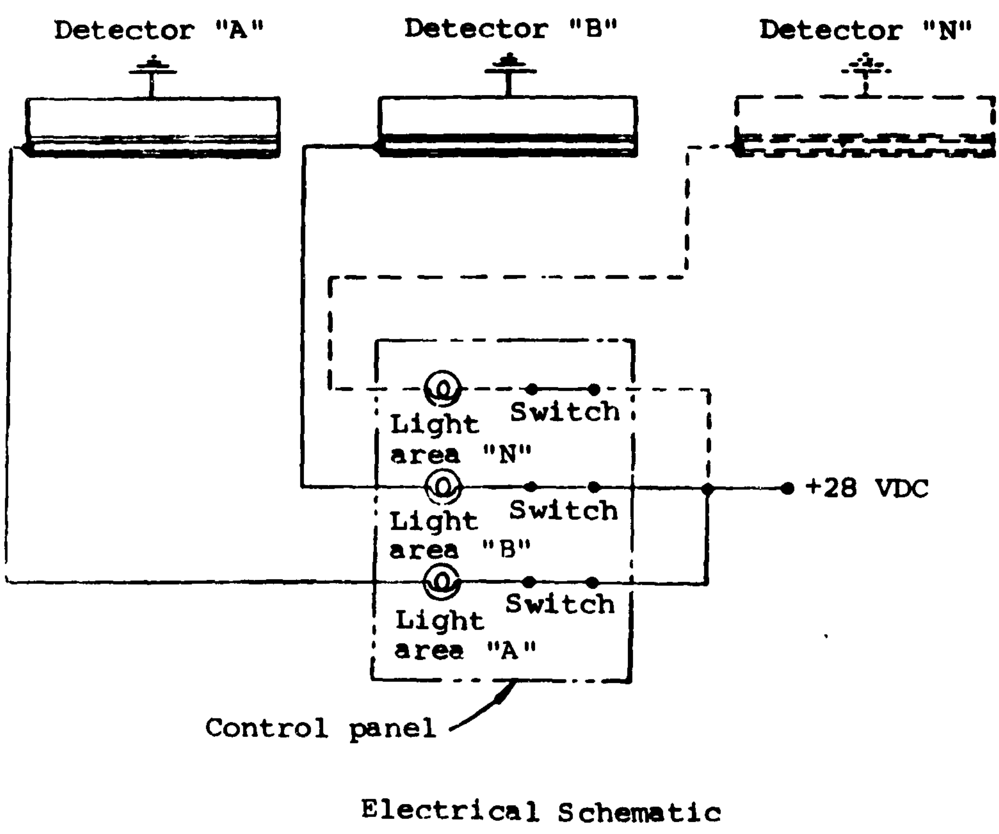
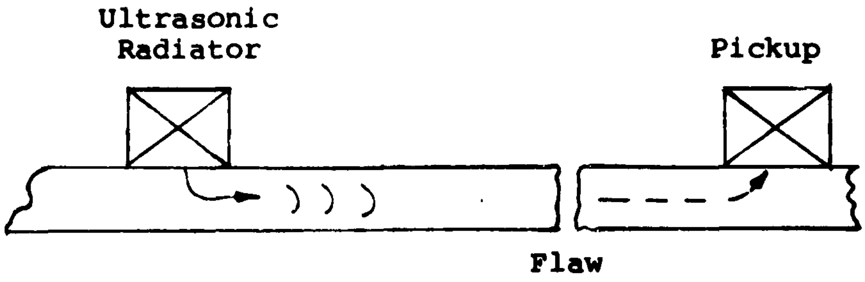
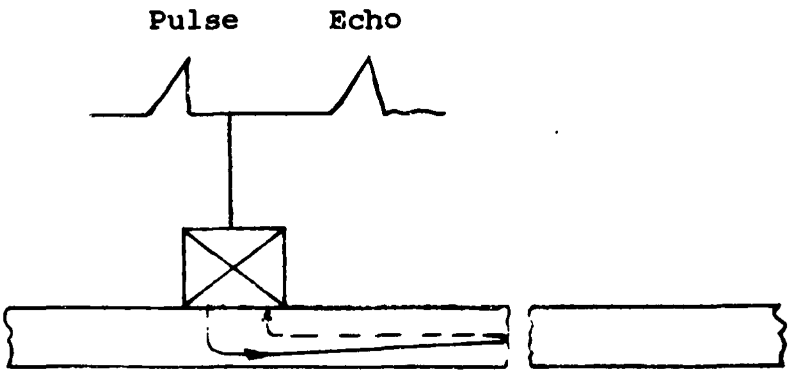


Figure 7 Continuity Sensor Electrical Contact Type Leak Detector - Locator (Ref. 1)



(a) Continuous Wave Detector



(b) Reflected Wave Detector

Figure 8 Ultrasonic Detectors

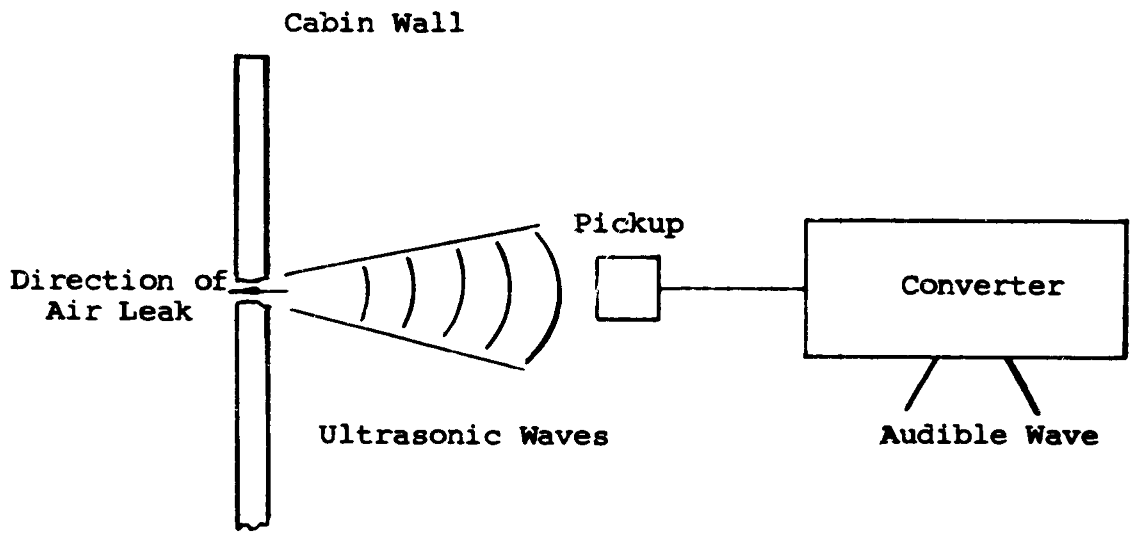
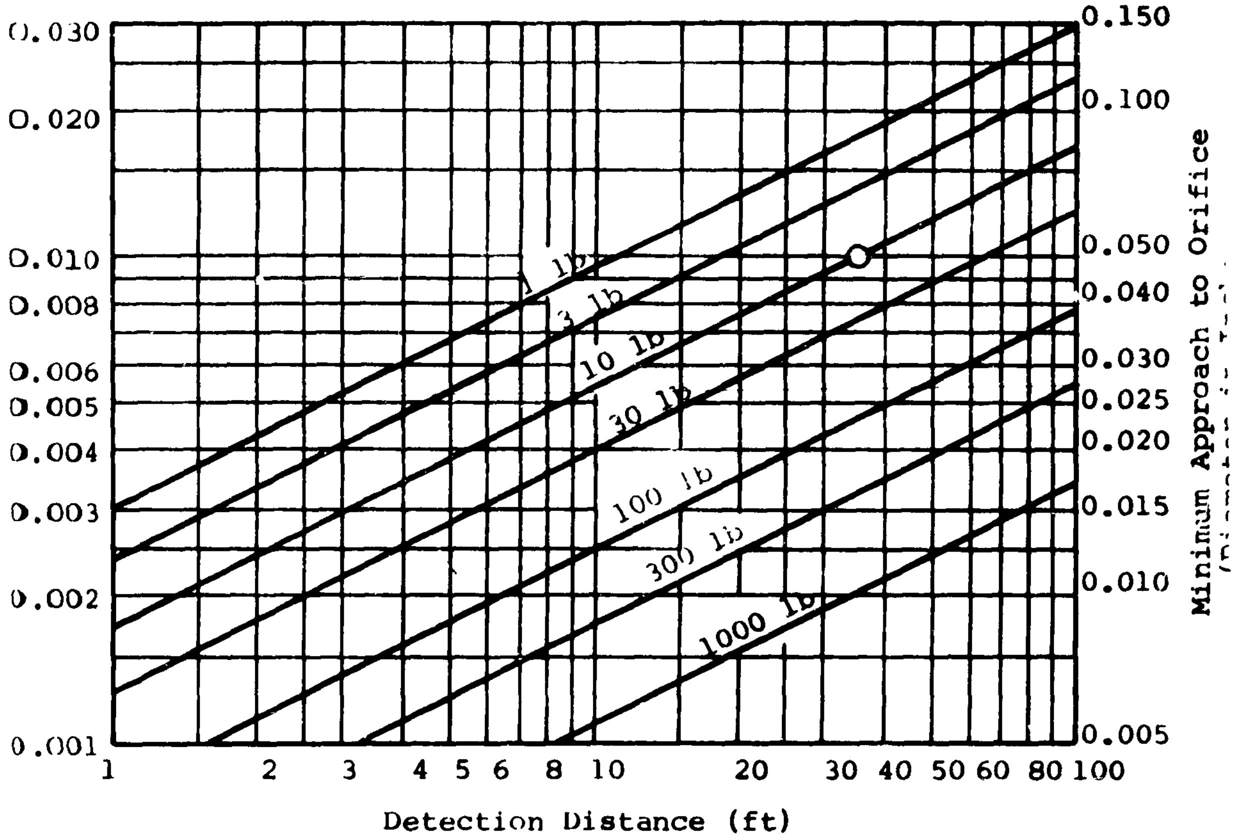


Figure 9 Acoustical Method of Leak Detection Using Delcon Ultrasonic Translator



Above graph correlates approximate orifice size, pressure and detection distance. A 0.010-in. diameter orifice in a container with more than 0.050-in. inside diameter, pressurized with air to 10 pounds per square inch can be detected at a distance of 35 feet directly in line with orifice. (Delcon Corp., Palo Alto, California.)

Figure 10 Ultrasonic Translator Typical Air Leak Sensitivity (Orifice Size) (Ref. 9)

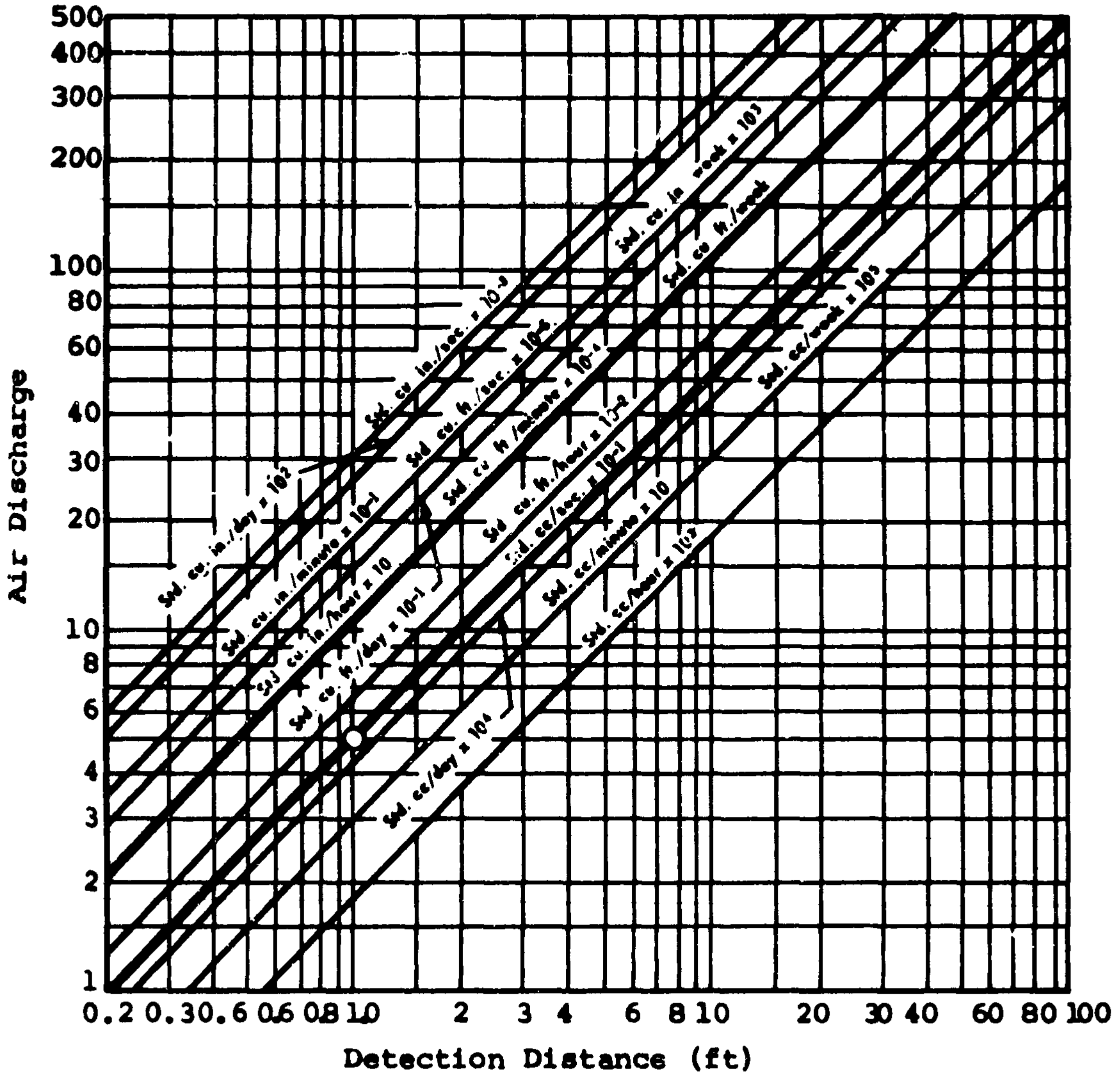


Figure 11 Ultrasonic Translator Typical Air Leak Sensitivity (Air Discharge) Delcon Corp. (Ref. 9)

(2) Laboratory Leak Detection Methods

Method 1. Spark Coil Over Outside of System

A high potential electrode is traversed over the outside of a system or component located within a vacuum environment. The leak is found by spark passing through the leakage flow or by a change in discharge color with materials such as ether, alcohol, or carbon dioxide.

Method 2. Pressure Rise Measurement

By monitoring the change in pressure in an isolated volume, the leakage rate may be calibrated.

Method 3. Detection of Tracer Gas with Thermal Conductivity or Ionization Gauge

Change in pressure within the system may be monitored using the thermocouple, Pirani or ionization gauge. A tracer gas applied to the exterior enters the leak and changes the thermal conductance or ionization current flow of the gas which was initially in the system. A rise in indicated pressure shows the presence of a leak. Similar techniques employing sealing substances on the outside of a system may be used also. In this case sealers such as water, lacquer, Glyptal, acetone, or ether clog the leak and cause a decrease in indicated pressure. Some of the sealers such as ether, provide a temporary seal while lacquer is permanent.

Method 4. Radioactivity Measurement

A radioactive material, such as Krypton 85, is allowed to enter a leak from the outside. Usually the external pressure is high. Leakage into the system is permitted for a given period after which the component is removed from the radioactive environment. The amount of radioactive material which has entered the component is measured by a scintillation counter.

Method 5. Halide Torch

A halide containing gas such as Freon is introduced into the system under pressure. A propane torch is used to heat a copper plate and the plate is traversed over the system. A leak is detected when the flame turns bright green.

Method 6. Hydrogen Leak Detector

Hydrogen tracer gas may be detected using an ionization gauge and a heated paladium diaphragm. Changes in gauge output show the amount of leakage.

Method 7. Halogen Leak Detector

Halide containing gases, when in contact with a hot platinum wire, change the positive ion emission of the platinum. Electrode current is measured, giving an indication of leakage.

Method 8. Helium Leak Detector

Leakage gases containing helium are ionized and the intensity of ion current produced is used to indicate the helium flow rate. Helium is separated from other gases present by a relative acceleration process. Since the mass of helium is low, it separates readily from other gases. Because of this property, helium is most commonly used with leak detectors which operate on this principle.

Method 9. Bubble Inspection

Bubble detection may be accomplished by applying pressure within the system and applying soap or other wetting fluid on the exterior. Bubbles are observed visually.

Method 10. Bubble Inspection (Immersed)

This method is similar to Method 9. In this case the component is submerged in a liquid, usually water. Bubbles are observed visually.

Method 11. Positive Displacement Devices

Leakage flow may be measured by positive displacement techniques providing it can be collected. The most common devices are:

a) Vane displacement meters. Instruments of this type are used to measure relatively large leakage rates. The rotational displacement of the device may be used to indicate total volume flow or flow rate.

b) Bellows displacement meters. The displacement of a pleated bellows or diaphragm may be used to measure volume change or, with suitable instrumentation, flow rate.

c) Glass capillary tubes. Very small diameter glass tubes containing a nonwetting fluid bubble may be employed to measure small leakage. The movement of the bubble must be visually observed.

Method 12. Rotameters

A tapered tube containing a flow is commonly used to measure large flow rates. The position of the float in the tube indicates a flow rate. Since the tube is tapered, the flow area about the float varies with position.

Method 13. Acoustic Detectors

Audio detection of leakage flow may be determined under certain conditions of flow. It is usually applied where large leaks are involved and choked or turbulent flow occurs.

Method 14. Chemical Reaction Methods

Coating of components with thin films subject to chemical change with the leaking fluid may be employed if the chemical change produces a discoloration of the film and is not detrimental to the component.

Summary of In-Laboratory Leakage Detection Instruments and Techniques

Source Locating Techniques

The source of gas flow may be readily located. The most sensitive methods employ the halogen or helium leak detector with a probe. A disadvantage is that a tracer gas is required. The bubble technique is satisfactory if sufficiently sensitive (10^{-4} atm cc/sec), the component is not too large, and the geometry is such that the leak is visually observable. Table II shows a summary of the methods which may be employed for gases.

Quantitative Leakage Measurements

Quantitative leakage measurements may be made at several locations in a system or component. Figure 12 shows schematically the principal locations of leakage measurements.

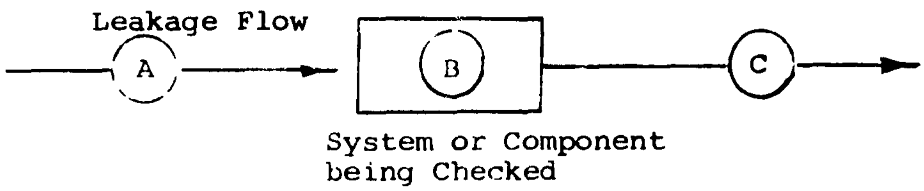


Figure 12 Location of In-Laboratory Leakage Measurement

Table II

Summary of Techniques for Locating

Sources of Gas Leakage

Method	Remarks
Spark coil	Difficult to apply to large objects. Requires insulation and vacuum environment.
Change in pressure	Requires trial and error application of sealants.
Halide torch	
Halogen leak detector	Probe attachment required.
Helium leak detector	Probe attachment required.
Bubble inspection (soap) Bubble inspection (immersion)	Bubble formation is time dependent and varies with leak rate. Satisfactory for leak rates of 10^{-4} atm-cc/sec.
Sonic detectors	Applicable to large leak rates or under special flow conditions. Influenced by background noise.
Chemical coating	Time dependent and limited by gas and coating material.

By using various techniques, some instruments may be employed to measure leakage by one or more of the following methods:

Method	
A	Leakage in
B	Leakage in minus leakage out and measured within
C	Leakage out

Some of these techniques are capable of measuring total leakage flow while others are capable of only sampling the total flow. The latter method is demonstrated by probing types of instruments. Table 3 tabulates the available instruments and their approximate ranges of sensitivity. The range of the helium leak detector may be extended up to 10^{-3} cc/sec by applying it in a system as shown on Figure 13 .

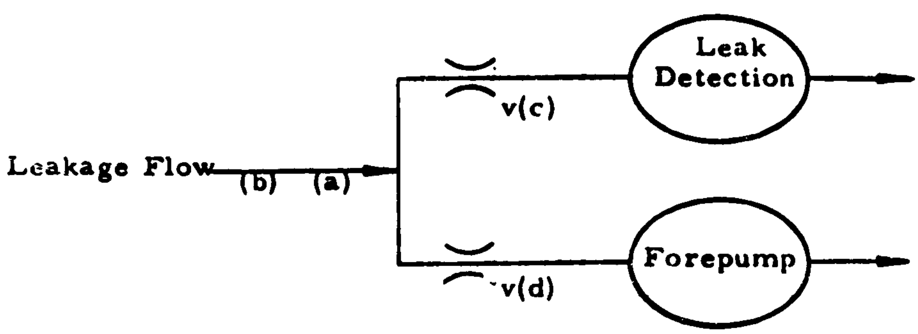


Figure 13 System for Extending the Range of the Helium Leak Detector

In the system shown, the pressure at point (a) is maintained constant. If the leak detector is calibrated, a calibrated leak may be placed at point (b). The ratio of flow division may be adjusted by varying throttling valves (c) and (d). The measuring system is then connected to the component being evaluated.

Table III

Summary of Leakage Measurement Techniques for Gases

Method	Technique (Note 1)	Leakage Rate Sensitivity atm cc/sec (10, 10, 10^{-1}, 10^{-3}, 10^{-5}, 10^{-7}, 10^{-9}, 10^{-11})	Remarks
2a	BD		Vacuum system applications. Maximum leakage flow depends upon pumping system, pressure and temperature.
2b	BD		Accuracy dependent upon pressure measurements. Susceptible to temperature changes. Constant leakage pressure cannot be maintained.
3	BD		Same as 2a above.
4	BD		Limited by the size of the component and influence of radioactivity.
6	BD		
7a	CE		Using probe attachment.
7b	BD		Installed within component
8a	CE		Using probe method.
8b	CD		
10	CD		Bubble rate of formation or bubble size necessary for accurate measurement.
11a	AD or CD		
11b	AD or CD		Depends on bellow size.
11c	AD or CD		Depends on tube diameter.
12	CD		

Note 1 - Technique Identification: A - leakage in, B - (Leakage in - leakage out), C - Leakage out, D - Total flow measurement, E - Partial flow measurement.

Bubble measurement techniques are probably the most widely used for general inspection. When accurate and reproducible quantitative measurements are required, other methods must be employed. Caution must be used in employing fluids which readily wet the leakage path. Surface tension effects occur, limiting leakage to levels well below the actual or operational level.

Most of the leakage instruments provide a readout in terms of leakage rate. Exceptions are methods 2, 3, and 11c. When using the pressure change method for gases, the sensitivity may be calculated from:

$$Q = \Delta V \Delta P / \Delta t \qquad (2)$$

where

ΔV = container volume
ΔP = pressure change
Δt = time increment

Temperature changes influence the accuracy of this method, depending upon the leakage rate and container volume. Another disadvantage is that a pressure change must occur. Thus, leakage information may not be readily correlated with other data.

(3) Leak Location Methods

Many of the leak detection techniques discussed above are applicable to leak location. In addition, visual aid techniques using fluorescent or colored materials and magnetic particles may be useful particularly if access to both surfaces of the pressure wall is possible. These methods are briefly discussed below.

(a) Fluorescent Penetrant Inspection

This method is used in industry for inspection of metallic parts for surface cracks or pores. It is a sensitive way of detecting minute cracks invisible to the naked eye. The procedure used is to apply a fluorescent liquid penetrant over the surface to be inspected, allowing it to enter any cracks or pores. The excess penetrant is removed and the area is viewed under ultraviolet (black)light. The penetrant seeping back from the cracks fluoresces and shows the defects in the inspection zone. A powdery developer which acts as a blotter is also used to aid the penetrant to emerge from the cracks.

In order for this method to be applicable, the general location of the leak must be known and the surface cleaned of particles that could keep and hold the penetrant. The penetrant must be applied by a brush-type applicator complete with penetrant reservoir in a thin, even coat. Since a water spray is not applicable to remove the excess penetrant, it can be removed with a wet or solvent soaked sponge. A developing powder in a colloidal suspension should be applied to the surface since a plain powder would contaminate the cabin with dust. Exclusion of normal light is necessary for viewing under an ultraviolet light.

The difficulties encountered with this method are the penetrant leaking through the crack or hole that is the subject for location. This would be enhanced by the pressure differential. Some penetrant will also volatilize. Thus, there will be less penetrant available to re-emerge from the crack under the action of the developer. Because of this, the time between excess penetrant removal and addition of the developer and drying should be as short as practical which may necessitate inspecting small areas at a time.

(b) Colored Penetrant Inspection

This method of inspection utilizes a colored penetrant, usually red, in a method similar to the fluorescent penetrant technique. In this case, however, ultraviolet light is not used as the penetrant. This method is not quite as sensitive because the indication is not as brilliant.

(c) Magnetic Particle Inspection or "Magnaflux" Inspection

In this method, a magnetic field is established in the test object, magnetic particles are then applied to the surface, and the surface is examined for accumulations of these particles. Since a magnetic material is required for this method to work, a thin magnetic membrane must be bonded to any non-magnetic structure.

(4) Leak Repair Techniques

The types of repairs required can be divided into three categories, according to the type of leak. These are (1) repairs of large punctures of the cabin wall, (2) repairs for small punctures and cracks, and (3) repairs of seal leakage. The methods for repairing these different types of leaks need not be the same, but it would be desirable, in order to reduce complexity, to utilize the same materials or methods to repair all leaks.

(a) Large Holes

1) Plug patch

- Self brazing plug
- Plug and sealant

2) Flat patch

- Welded patch
- Adhesive bonded patch
- Mechanically fastened patch (rivets, bolts)

(b) Small Holes and Cracks

1) Sealant

- Brush type
- Spray type
- Putty type

(c) Seal Failure

1) Seal replacement

2) Seal repair

Table IV taken from Reference 1 is a summary evaluation of some manual repair techniques which are applicable to sealing of punctures and cracks.

(d) Self-Sealing Methods

A self-sealing layer bonded to the pressure wall provides an automatic repair method for smaller punctures. The advantages of such a method are self-evident. It eliminates the need to detect, locate, and subsequently repair the small punctures. Repair will be almost instantaneous, and very little atmosphere will be lost. However, in the design of a self-sealing layer, there will be a maximum size puncture that can be sustained and sealed. Punctures above this size will create cabin leakage. If provisions are to be made for the repair of these larger punctures, a leak detection and location system of the type discussed previously will be required. Therefore, the real benefit of a self-sealing cabin wall is the automaticity of repair. That is for many punctures, the crew will not be required to locate the leak, or repair it.

Several concepts for self-sealing of pressurized structures exist. These design concepts contain some of the following self-sealant materials.

Mechanical Self-Sealants	Chemical Self-Sealants
Flexible foams	Latex sealants
Microballooms	Swelling sealants
Cured elastomeric sealants	Chemical reactant sealants

Table IV

Summmary of Manual Repair Methods

Repair Method	Application	Remarks
Patch, metal mechanically fastened, sealant backed	For repair of large punctures where cabin is pressurized and rework is allowed	1. Only method applicable to odd size punctures, tight corners - all situations short of repair
Patch, metal, bonded		2. Hard to fit contoured wall
Patch, elastomeric bonded		3. Same as 2
Plug, elastomeric or metal bonded and sealed		4. Cannot be used in every case
Plug, metal self-brazing		5. Same as 4
Putty sealant - curable two-part compound	Small punctures and cracks - cabin pressurized, no rework of damaged area	6. Forms tough, durable seal
Putty sealant - curable two-part compound		7. Same as 1 - epoxy type has unexcelled strength and adhesion
Liquid type - cures to form film		8. Good for only the smallest holes and cracks
Patch, elastomeric, adhesive sealer backed		9. Reliability and application low because of interference from protruding edges of puncture

Table IV (Cont.)

Repair Method	Application	Remarks
Patch, hollow, adhesive sealer backed	Small punctures and cracks - cabin pressurized, no rework of damaged area	10. Tight corners problems
Patch, metal depressed center, gasket adhesive sealer		11. Tight corners problems
Plastic sheet adhesive backed		12. Good for only smallest punctures and cracks
Plug, elastomeric and sealant		13. Jagged punctures problems
Putty sealant - curable one-part compound	Repair of seals	
Putty sealant - curable two-part compound		
Liquid brush, roll or spray-on type cure to form film		

SECTION III

GENERAL ENVIRONMENT

The purpose of this section is to summarize currently available information on the space environment and to identify and quantify these environmental factors which affect the selection of a seal material or configuration for a particular space application.

1. THE NATURAL SPACE ENVIRONMENT

The term "natural" is used here to define those environmental properties which exist whether a space vehicle is there or not. Those environmental effects caused by the presence of the space vehicle are termed "induced" and are discussed in Section III-2 following.

a. Pressure

The pressure of the atmosphere at a given altitude above the earth is not invariant but subject to a number of dynamic effects. However, good averages will suffice for this program. Figure 14 (Ref. 1) shows the average atmospheric pressure with respect to altitude up to about 400 miles. The pressure decreases with altitude from the average of 760 mm Hg at sea level to about 10^{-6} mm Hg at 125 miles. Reference 2 lists 3.6×10^{-9} torr as the most severe vacuum likely to be encountered in a 200- to 300-nautical mile orbit about the earth. Above 4,000 miles altitude, the pressure is less than 10^{-12} mm Hg; and in interplanetary space, the pressure is thought to be 10^{-16} mm Hg, which corresponds to a density of 4 molecules/cc.

In the orbital range of about 100- to 400-miles altitude, pressure estimates given by different authors differ by about one order of magnitude. In addition to the difficulties in measuring pressure (or density) in this thin atmosphere, the sunspot cycle affects the density (pressure) measurably. This is illustrated graphically in Figure 15 (Ref. 3).

b. Radiation

Because of the shielding effect afforded by the earth's atmosphere, much of the radiation existing beyond the atmosphere cannot be measured on the surface of the earth. The radiation components of the space environment are sundry, complex, and in some cases, unknown. Theoretical models have been proposed for some types of space radiation, and radiation data have been obtained using rockets and other experimental means. The data presented here is based on the best presently available information; new data, particularly that being collected by the Explorer

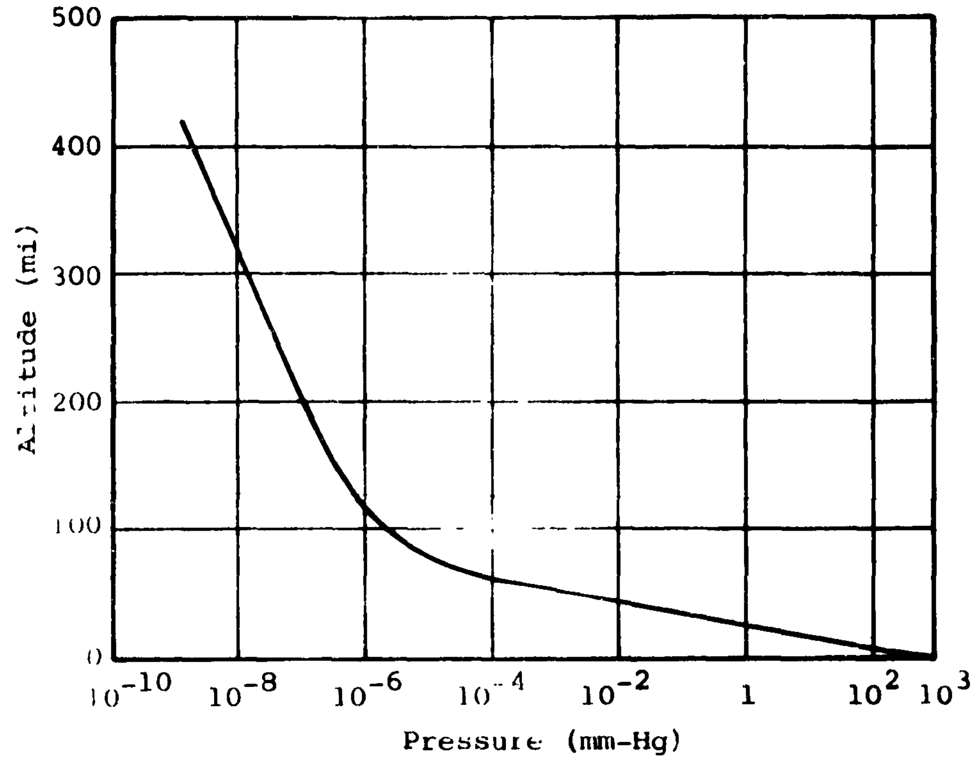


Figure 14 Pressure vs. Altitude Above Earth

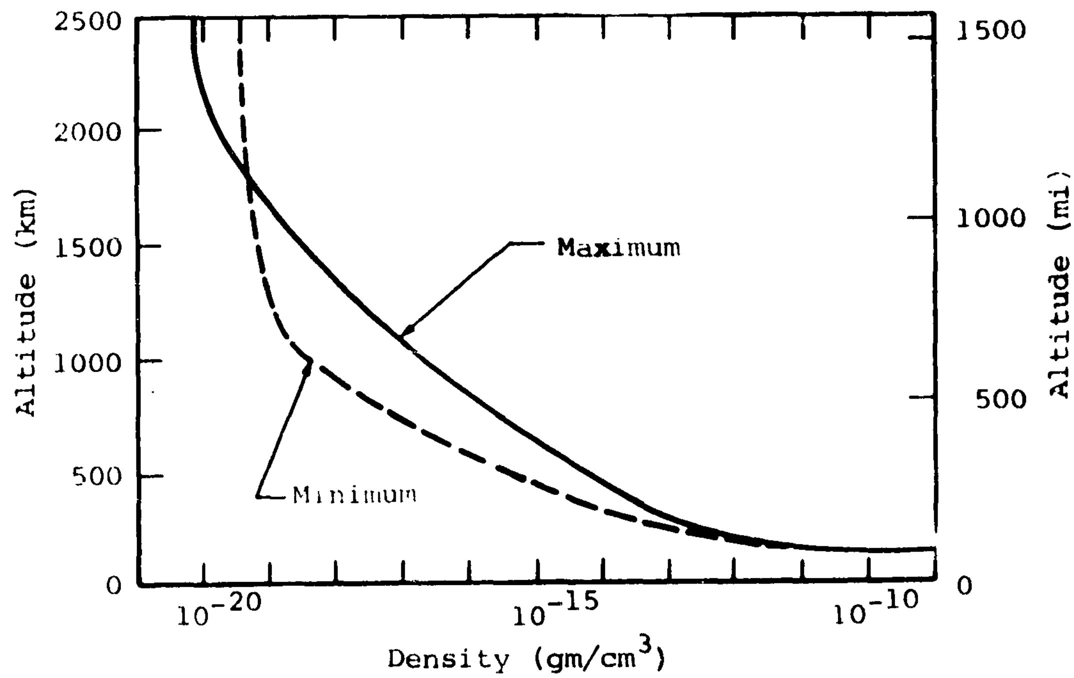


Figure 15 Average Daytime Atmospheric Densities at Extremes of the Sunspot Cycle

series of space probes, can change these values considerably in some cases. The values presented are, in general, for near earth space; little data is available for deep space.

A summary of the various space nuclear radiation components encountered in a 200- to 300-nautical mile orbit are presented in Table V (Ref. 2). These data are an integrated yearly estimate, and are thus influenced strongly by short periods of high activity. So-called normal levels would be much lower. The values are based on the incident surface energy received on each square centimeter of space vehicle area. An explanation of the terms in the table is given in the ensuing discussion.

Table V

Total Maximum Surface Absorbed
Dose Rates vs. Time
(Orbit of 200 to 300 nm)

Source	Orbital Inclination 28.5° (rad/yr)	Orbital Inclination 90° (rad/yr)
Solar flare events	30.0	450
Electron belt	3.0×10^6	10^6
Proton belt	0.3×10^6	0.20×10^6
Miscellaneous radiation	145.0	10^8
Total	3.3×10^6	1.01×10^8

(1) Solar

The bulk of the energy in the solar electromagnetic spectrum lies between the wavelength limits of 0.3 and 4.0μ ($1\mu = 10^{-4}$cm $= 10^4$ Å), with approximately one percent of the energy lying beyond these limits. Figure 16 (Ref. 3) shows the distribution of energy in the solar radiation incident on the earth's upper atmosphere at the mean distance from the sun. The solar constant is the total solar irradiance; it is equal to the area under the curve of Figure 16, and has the value of 0.140 w/cm^2 (443 Btu/ft^2-hr).

(2) Thermal

The visible and infrared (the ultraviolet not included) portion of the solar spectrum is well approximated in spectral quality by the radiation emitted by a 6000°K blackbody. This will be felt by a space vehicle as solar thermal

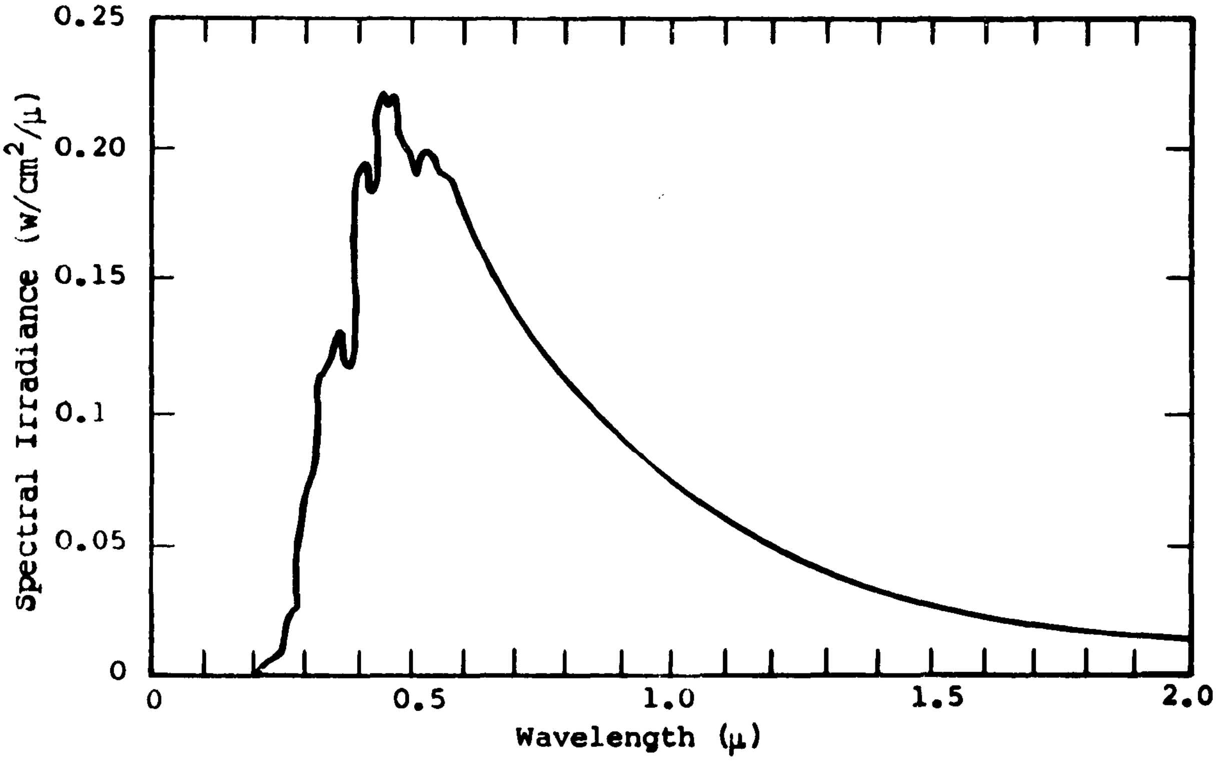


Figure 16 Solar Spectral Irradiance Outside the Earth's Atmosphere at the Earth's Mean Distance from the Sun

radiation. The product of the vehicle's surface absorptivity (to 6000°K blackbody radiation) and the solar constant will be equal to the solar thermal input to the side of the vehicle facing the sun. The portion of the space vehicle not facing the sun or the earth will radiate thermal energy as a function of its local temperature and its surface emissivity at that temperature, to deep space, which acts as a blackbody at about 3°K. The net thermal radiation (difference between input and output) at a given space location determines the local space vehicle surface temperature whether the heat flow is into the vehicle or out of it. Space vehicle temperatures are expected to lie in the range between -100°F and 300°F. In the interior of the vehicle, thermal control systems will hold temperatures to within a few degrees of a preselected temperature based on human or equipment requirements.

(3) Ultraviolet

The ultraviolet radiation of the near-earth space environment will be higher during solar flare activity than during quiescent sun periods. Since the solar flare events are known to be cyclical in character, the exact ultraviolet intensities incident on space vehicles will be a function of the operational time period of the vehicle.

Ultraviolet radiation has wavelengths from 0.01 to 0.4μ. Since the solar energy less than 0.4μ is about 9 percent of the total solar constant, the integrated intensity from the ultraviolet component is 12.6 milliwatts/cm^2 for the "quiet sun."

The solar spectrum below 0.3μ must be obtained from rocket observations as virtually none of this radiation penetrates the earth's atmosphere. Below 0.22μ, the solar spectral irradiance curve is well approximated by the radiation which would be received from a blackbody source the same size as the sun and having a temperature of 4500°K. In addition to this continuum radiation, there are a number of emission lines which contribute only a small amount of energy compared to the continuum above about 0.14μ.

(4) Solar X-Rays

Although the major portion of the electromagnetic radiation from the sun is not ionizing in nature, a very small portion (about 0.1 percent of the solar constant) lies in the soft X-ray region of a few kilovolts. On this basis, the surface dose rate is estimated to be about 10^6 roentgen/hr and higher after solar flares. Since this X-ray energy is absorbed strongly by materials, the dose rate in the interior of the space vehicle will be negligible.

(5) Solar Flares

The previous discussion has been concerned with the electromagnetic radiation emanating from the sun. The sun also gives off very high-energy particles whose characteristics are very similar to cosmic rays. The flux of these particles, observable near the earth, is highest about an hour after the first detectable signs of intense solar surface activity (called a solar flare).

Some data exists on high-energy electrons and electromagnetic radiation associated with solar flares, but the majority of the activity is due to intense fluxes of energetic protons (hydrogen nuclei). The proton flux arrives on the sunlit hemisphere of the earth and generally lasts between 10 and 100 hours with an intensity decay dependence with time of about t^{-3}.

Because of the magnetic field of the earth, the protons (being charged particles) are deflected away from the equatorial regions and are most intense in the polar cap regions. Most of the solar flare proton events observed have involved non-relativistic protons which are stopped in the earth's atmosphere, but relativistic protons have been observed at the earth's surface. Fluxes may be as high as 10^4 protons/cm^2-sec for large events. Average dose rates may range from 1 to 100 roentgen/hr and the total dose would range from 10 to 10^3 roetgens.

(6) Solar Wind

The solar wind is regarded as a continuous flux of particles (protons and/or electrons) from the sun in its normal quiescent state. The distribution of solar wind particles is believed to obey an inverse square law with the sun acting approximately as a point source. This distribution would be perturbed by the earth's magnetic field. The solar wind would be prevalent at altitudes of several earth radii or greater, and thus would not be felt by an orbiting space vehicle.

c. Albedo and Earth Radiation

Temperatures of near-earth satellites are determined to a large extent by the thermal radiation interchange between the earth and the satellite and by the surface absorptance-emittance characteristics of the vehicle. Heat is radiated to the spacecraft directly from the earth's surface and reflected (albedo) from the sun off the earth's atmosphere. The thermal radiation from earth to the space vehicle is about twice as great with clear skies, but the albedo radiation is about 3 times as great with cloudy skies as with clear skies. The relative cloudiness affects thermal radiation more than the other radiation components.

The albedo (reflected solar) radiation contains several other important components in addition to thermal radiation, while the earth radiation consists entirely of infrared energy (thermal), nearly all at wavelengths longer than 4.0μ. The other components of albedo radiation include ultraviolet, neutron, proton, and bremsstrahlung flux. The spectral intensity of albedo electromagnetic radiation is highest in the range between 0.29 and 0.4μ, the ultraviolet region. Particulate albedo radiation is discussed below.

(1) Albedo Neutrons

The interaction between primary cosmic rays and the atmosphere produces neutrons, some of which recoil away from the earth. An upper limit of 0.8 neutrons/cm^2-sec at 200-nm altitude has been established with an energy peak in the 1-10 ev region. This produces a negligible dose.

(2) Albedo Protons

In addition to recoil neutrons, protons are also produced by cosmic ray primaries. At 200 nm, there exists a flux of about one proton/cm^2-sec between energies of 1 to 10 mev. This produces a negligible dose.

(3) Bremsstrahlung Flux

Electron interaction with the atmosphere produces a low energy (20 kev) gamma radiation. The expected flux at 200 nm is given by various references to be about 10^4 photons/cm^2-sec. This yields an expected maxinum surface dose rate of 10.7 millirad/hr, or 93.6 rad/yr. This Bremsstrahlung radiation is readily absorbed by the spacecraft walls where it is subsequently dissipated as heat.

d. Other Natural Radiation

The other types of radiation to be described are mostly particulate in nature and are generally highly penetrating. Some of these phenomena are highly localized and can be avoided by not entering the zones where they are prevalent.

(1) Cosmic Radiation

Except for such localized effects as the deflections caused by the earth's magnetic field, the distribution of primary cosmic particles in space is essentially isotropic and uniform. The normal primary cosmic particle flux in free space is about 2 particles/cm^2-sec, and its composition can be described as abcut 90 percent protons, 10 percent alpha particles (helium ions), plus very small fractions of heavier ions having atomic numbers up to about 30. These cosmic primaries are moving with relativistic or near-relativistic velocities; their energy spectrum is very high, mostly from 1 to 10^{10} bev.

Most of the cosmic rays impinging on a space vehicle will traverse with very little interaction or loss of energy. However, these are secondaries formed by cascade shower phenomena and by high-energy nuclear interactions such as spallation and star formation. The effective ionization dose rate due to cosmic primaries is about 10^{-4} roentgen/hr, and the approximate effective dose due to secondaries produced in a space vehicle or in the atmosphere is about 10^{-3} roentgen/hr.

The earth's magnetic field causes considerable deviation in cosmic ray flux, so that in an earth orbit the dose will vary from about 8 to 50 rad/yr, depending on altitude and orbital inclination. Shielding against cosmic ray primaries is nearly impossible due to the high penetration of the primaries and the secondary radiation, but the dose rates are low enough to be tolerated by most materials except for very long periods of time.

(2) Trapped Radiation (Van Allen Belts)

The spatial distribution of the Van Allen belts may be visualized as a torroidal configuration encircling the earth about its geomagnetic equator. The Van Allen belts can be considered as a proton belt, centered around 2,000 miles above the magnetic equator, and an electron belt, centered around 10,000 miles; these belts intermingle at lower altitudes.

The maximum proton flux at the heart of the proton belt is estimated to be 3×10^4 protons/cm^2-sec. This flux corresponds to a dose rate of about 30 roentgens/hr. Vehicle interior dose rates for protons is not much different from the surface dose rate although present data are not adequate for an accurate comparison.

The electron flux at the most intense portion of the electron belt is 2×10^8 electrons/cm^2-sec, and the corresponding surface dose rate is about 10^5 roentgen/hr. The maximum vehicle interior dose rate in this outer belt region ranges from 10 to 100 roentgen/hr.

While the proton belt is fairly stable in position (with respect to the earth) and flux rates, the electron belt is suspected by many investigators to shift radically in flux level and in energy spectrum with solar activity and associated phenomena such as magnetic field perturbations. Estimates of the total yearly surface dose in a 200- to 300-nm orbit are given in Table V.

(3) Auroral Radiation

Auroral radiation fluxes are found most frequently between 65 and 70 degrees north and south magnetic latitudes. The loci of the auroral radiation zones may be visualized as crown-like configurations sitting over the polar caps. Polar orbits of earth satellites include four traverses through the auroral region per orbit, while equatorial orbits do not include the auroral regions. The occurrence of auroral radiation is much more sporadic than the Van Allen radiation.

Electron fluxes measured during auroral storms are known to be as high as 10^{11} electrons/cm^2-sec. Corresponding to a surface dose rate of 10^8 roentgen/hr. These maximum fluxes are believed to correspond to sharp spikes and sheets of auroral radiation and are not believed to pervade the entire region. Because of the sporadic nature and spatial distribution of aurora, it is generally agreed (Ref. 2 and 3) that the statistical average surface dose rate per year would be about 10^7 to 10^8 roentgen. The low-energy (mostly <50 kev) electron primaries are not expected to penetrate the typical vehicle skin. Secondary bremsstrahlung radiation reaching vehicle interiors is estimated at about 10 to 15 roentgen/hr. The statistical dose rate received over several days orbiting will be dominated by the dose received during active auroral displays.

Auroral protons are much lower in flux than the auroral electrons. The flux is about 10^5 protons/cm^2-sec with energies ranging up to about 650 kev. The corresponding surface dose rate is about 500 roentgen/hr in active aurora, and the internal dose due to protons is negligible.

Shielding vehicle interiors against auroral radiation, both primary and bremsstrahlung, is relatively simple using multiple element or laminated materials, but vehicle exterior surfaces can be damaged considerably from long exposures to the high electron fluxes.

e. Meteoroids

The discussion presented in this part on meteoroids is abstracted almost entirely from Reference 4. It is a good summary of and in close agreement with the material presented in References 1, 2, 3, and 5. More detailed descriptions of the meteoroid environment are presented in Reference 1 and 5. The ensuing discussion delineates the "cloud" of meteoroids surrounding the earth to about the cis-lunar distance or 60 earth radii. Flux rates for meteoroids in interplanetary space are considered to be much lower since meteoroids become trapped in the earth's gravitational field.

(1) Flux Rate

Observations on the meteoroid flux about the earth have been made for larger meteoroids through the utilization of various photographic and radar techniques from ground-based stations. Measurements of the flux rate of smaller meteoroids have been made primarily through the use of various measuring devices carried by rockets and satellites. The reduction of all this raw observation data to a useful form is based upon certain assumptions of meteoroid physical characteristics (e.g., density, luminous efficiency, etc.). In the case of the smaller meteoroids, data reduction is complicated by impact interactions with other satellite instrumentation. The uncertainties involved in meteoroid observations have resulted in estimates of meteoroid influx rates which differ by orders of magnitude. The two curves shown in Figure 17 are intended to bracket the average actual meteoroid distribution in space. The actual distribution is, however, quite nebulous since it is believed to vary with both time and with location in the solar system. The various proposed meteoroid influx rate relationships, including those shown, may be expressed by an equation of the form

$$\phi = K/m \qquad (3)$$

where ϕ = flux in particles/unit area/unit time, having a mass greater than m
K = a constant
m = meteoroid mass

It is generally agreed, as the above relationship indicates that the number of meteoroids increases as their mass decreases. From the standpoint of providing meteoroid protection capabilities in spacecraft designs, the large meteoroids and asteroids may be neglected because of 1) their rarity, and 2) the impracticality of attempting to provide protection against such an impact force. However, compartmentalization can isolate and minimize large meteoroid damage. The very small meteoroids (micron size) may cause erosion of surface materials. It is estimated that the intermediate sizes (10^{-3} to 1 centimeter) will present the greatest hazards from skin penetrations.

(2) Velocity

There is general agreement that the absolute velocity range of meteoroids is between about 11 and 73 km/sec. The lower velocity limit is determined by the velocity a particle would attain if it fell from a great distance under only the influence of the earth's gravitational field. The upper velocity limit is based upon the assumption that the earth runs head-on into a particle which is in retrograde orbit around the sun and is determined by adding the earth's orbital speed to the maximum orbital speed of this retrograde particle

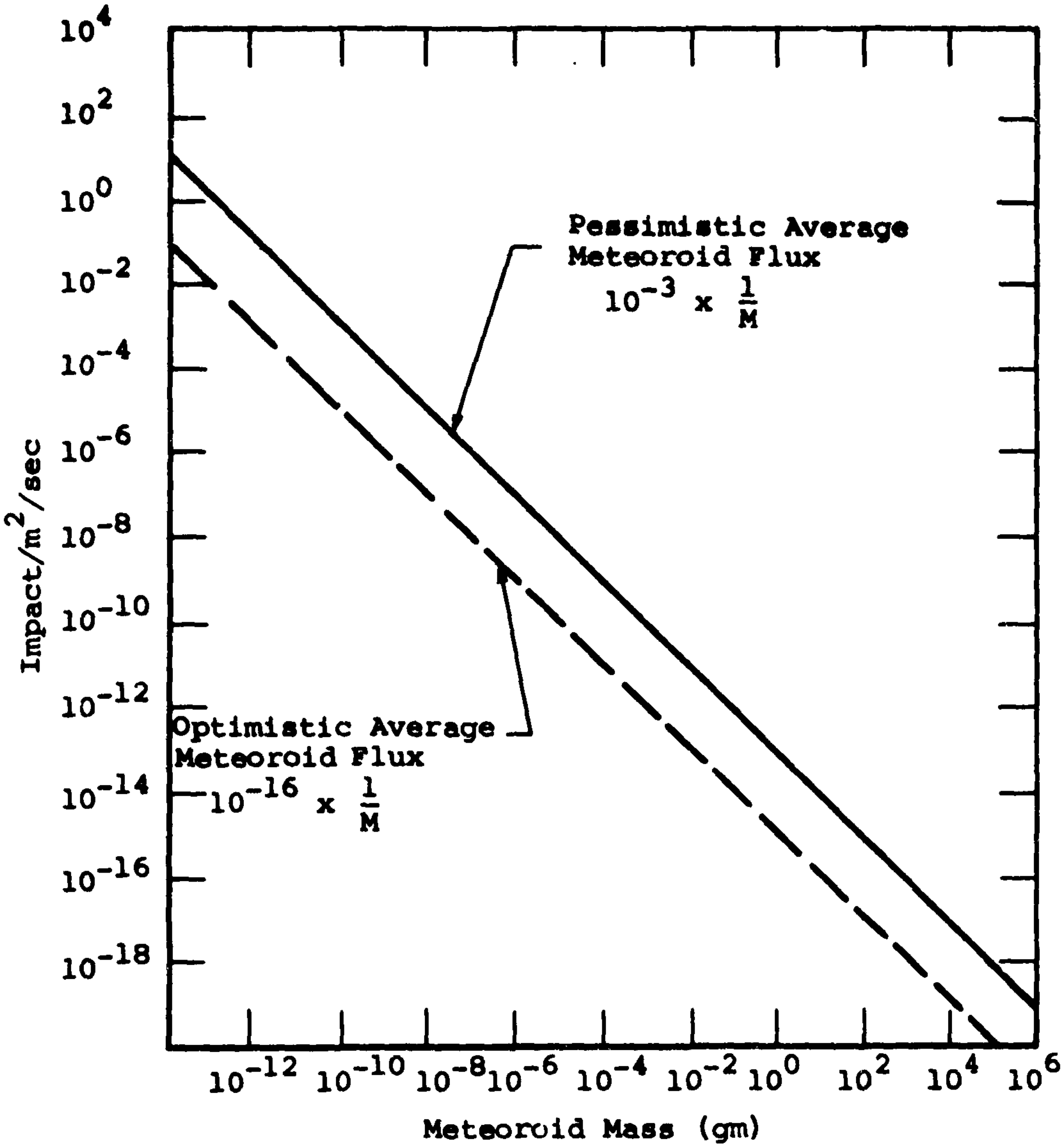


Figure 17 Meteoroid Frequency as a Function of Meteoroid Mass (Ref. 4)

at the earth's radial distance from the sun. It is further generally agreed that the velocities of the smaller mass particles probably lie near the lower velocity limit. Whipple's 1961 estimate (assuming the mass of a zero visual-magnitude meteor to be 2.0 gm) proposes that an average velocity of 15 km/sec be used for particles up to $10^{-7.7}$ gm.

2. THE INDUCED ENVIRONMENT

Induced environments are created by the vehicle system itself, from internal energy sources, or by reaction with the natural environment. Specific definition of induced environment is thus highly dependent on particular characteristics of each vehicle system. Careful design of space vehicle systems will assure that the effects of the anticipated induced environments will be within tolerable limits, particularly on manned missions. The following discussion, abstracted mostly from Reference 6, is necessarily general in nature and qualitative rather than quantitative, although illustrative values are given as an indication of the order of magnitude of the effects.

a. Kinematic Environment

Kinematic environment is that which is produced by virtue of motion in a mechanical system. Although this subject is treated here under the separate headings of acceleration, shock, and vibration, these variables do not occur independently in a real vehicle system.

(1) Sustained Acceleration

Typically, high-force sustained accelerations are encountered for boost and re-entry phases of space flight. Duration of exposure to sustained acceleration during boost varies from a few seconds to about 200 seconds per stage. Typical sustained launch and boost accelerations predictable for the next decade are: 8g for large vehicles (for the longest times); 20g for medium sized; and 50 to 100g for small vehicles (for the shortest times). Manned vehicles will be limited to peaks of 8 to 12g for short durations, and less for longer durations.

Maximum acceleration (deceleration) attained during atmospheric re-entry is dependent only on path angle, initial velocity, and characteristics of the atmosphere. For instance, vehicles entering the atmosphere vertically from space can encounter accelerations of 300g, while vehicles entering at 15 degrees below the local horizon will experience 8.5g deceleration.

The condition of "zero gravity" is a rather special case of sustained acceleration and is generally associated with an orbiting vehicle whose radial acceleration just balances the earth's gravitational force, or with a vehicle travelling in deep space.

(2) Mechanical Shock

Mechanical shock is not easily distinguished mathematically from vibration or acceleration; the difference is one of degree rather than a change of parameters. Energy applied impulsively to a system is described as shock; energy applied in a periodic or quasi-periodic manner is called vibration; and energy applied relatively continuously in one direction is termed sustained acceleration.

Engineering terms and units used to describe shock include the input or response pulse shape, duration, and amplitude, the latter usually in peak g's. In general, flight conditions will be less severe than vehicle environment shock conditions during transportation, handling, or other ground operations. Significant shock environment will exist, however, during propulsion stage ignition and separation. Shock amplitudes as high as 200g have been recorded during this sequence. Landing shocks of vehicles designed for soft landings have recorded 17g on the fuselage. Shock levels in the foreseeable future are not expected to deviate appreciably from these values.

(3) Vibration

The vibration environment is unique to each vehicle and cannot be accurately predicted. This environment may be expressed in terms of power spectual density, $(\bar{g})^2$/cps, which is the square of the root-mean-square acceleration divided by the nominal bandwidth in cycles per second. The value of this quantity varies from $30(\bar{g})^2$/cps near the rocket motor of small vehicles to $1.5(\bar{g})^2$/cps for Atlas or Titan class vehicles.

b. Aerodynamics Heating and Internal Heat Sources

The source of high thermal energy are:

Aerodynamic heating during exit and re-entry. Possible skin temperatures of 1200 to 1400°F. Rate of temperature change of 35°F/sec can be expected.

Combustion of fuels, 3000 to 5000°F or higher

Cryogenic fluids

c. Nuclear Radiation From On-Board Sources

Penetrating gamma and neutron radiation

Neutron flux (7.75×10^{16}/sec) per megawatt of operating power

Gamm flux (1.91×10^{17}/sec) per megawatt of operating power

SECTION IV

PROPERTIES OF RUBBER AND PLASTIC SEAL MATERIALS

The design of seals necessitates the selection of an appropriate seal material. The physical, chemical, and thermal properties of the material as well as the effect of the environment (discussed in Section III-2) dictate the choice. Thus, it is appropriate to include discussions and tables of material properties for both rubbers and plastics which affect the choice of material for a sealing application. Properties of metals are not included because the majority of seals encountered in space station design are not metallic. Furthermore, the properties of metals are well defined and readily obtainable.

1. RUBBER

The problem of selection of elastomers is difficult. Familiar engineering terminology when applied to natural or synthetic rubbers often has a different meaning than the conventional word usage. In order to select a rubber material, it is necessary that the characteristics of the material be understood.

Tensile strength, in rubber, refers to the force per unit of original cross section that was applied. A typical stress-strain curve is shown on Figure 18 (Ref. 7).

Modulus is the tensile stress that will produce a given amount of extension. In rubber, the stress-strain relationship is not proportional. Therefore, the modulus of an elastomer refers only to a single point on the stress curve.

Hardness is a measure of the resistance of rubber to deformation. The units for hardness are the Durometer numbers. It is measured by pressing a ball or blunt point into the surface and measuring the amount of depression.

Resilience is the property of rubber which enables it to return to its original shape after having been deformed. It usually is expressed in percent of the energy returned after the removal of the stress which caused deformation.

Hysteresis represents energy lost per loading cycle. The stress-strain curve of a rubber compound plotted for increasing and decreasing loading conditions shows an energy loss. This can be seen from a typical curve shown on Figure 19. This is generally due to the conversion of mechanical energy into heat.

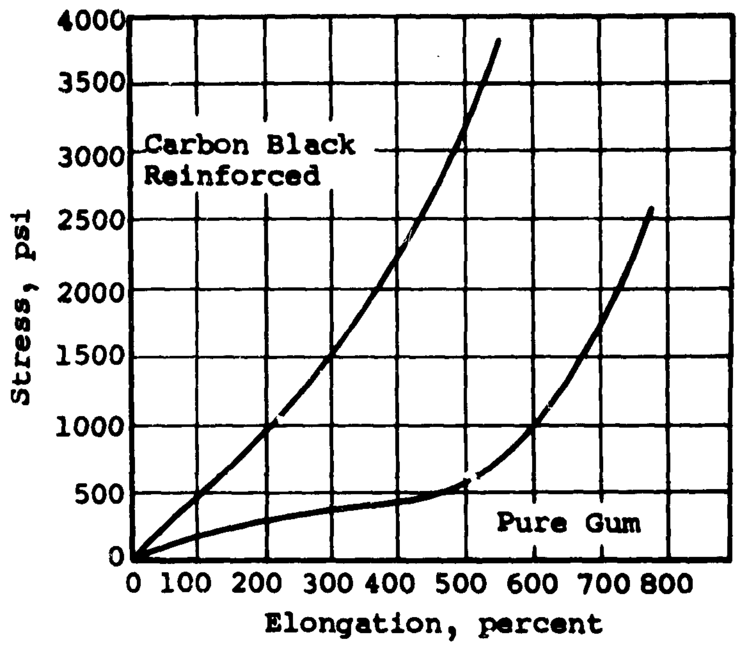
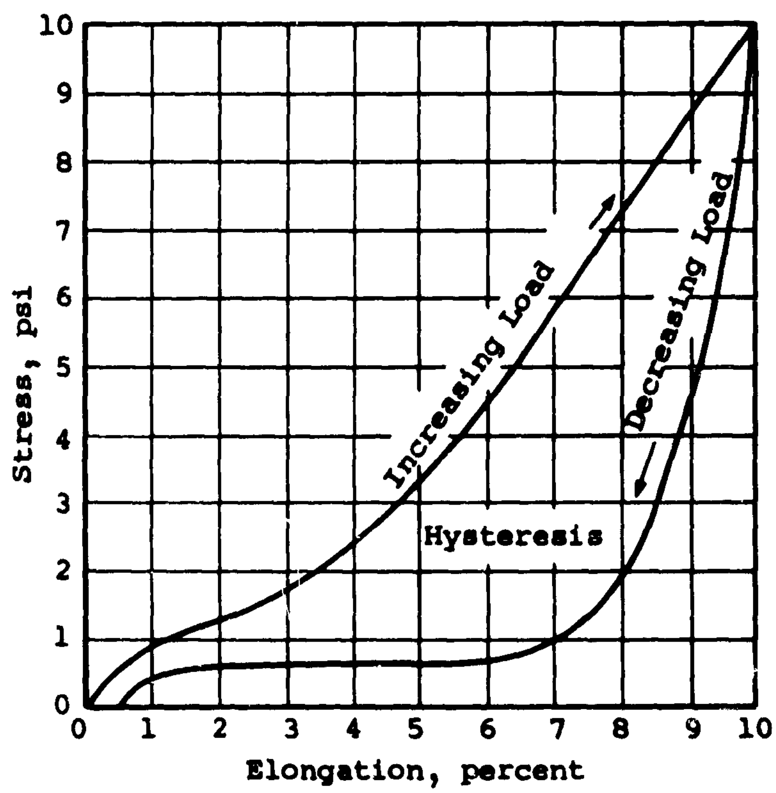


Figure 18   Typical Stress-Strain Curves for Soft Vulcanized Natural Rubber (Ref. 7)



—gure 19 Hysteresis Effect of Soft Vulcanized Natural Rubber (Ref. 7)

Permanent set is the deformation of a rubber material that remains after a given time when a specific load applied for a given time has been released. Normally, it is specified whether the set has resulted from tension, compression, or shear forces.

Stress relaxation refers to the loss in stress when the material is held at constant strain over a given time period.

Creep of rubber is the change in strain when the stress is held constant. Both stress relaxation and creep are expressed as percent change in deformation.

Abrasion resistance refers to the resistance of a rubber composition to wear and is measured by the loss of material when it is brought into contact with a moving abrasive surface.

Tear strength is a measure of the force required to propagate a cut in a normal direction to that of the applied stress (the force necessary to initiate tearing).

The shape factor is the change in the compression-deflection relationship because of the shape of the part. For pieces having parallel loading faces and sides normal to these faces, the ratio of face load to the side area provides a measure of the degree of compressibility. Since rubber is virtually incompressible, the ability of the material to compress depends on the amount of side area that is free to bulge.

Thermal properties of natural and synthetic rubbers that are important include coefficient of expansion and the "joule effect." The coefficient of expansion varies, depending on the kind and amount of filler added to the gum rubber. The more filler that is added, the lower the coefficient. The expansion of rubber is approximately one order of magnitude greater than steel. The "joule effect" is a phenomenon based on the fact that the modulus of elasticity of rubber increases with a rise in temperature. The rubber has to be under strain for this effect to occur. This effect is rather important in an application where strain and heating may occur. For example, O-rings used to seal a rotating shaft become heated and attempt to contract. Thus, more heat is generated and eventually results in seal failure.

Aging describes the deterioration of rubber with the passage of time. The changes which take place in aged rubber can be described in three ways (Ref. 7).

> Disaggregation resulting in a reduction in average molecular weight. This produces a "softening" of the elastomer and is also referred to as chain scission. It is caused by oxidative and/or thermal chain rupture and depolymerization of polymeric structures.

Aggregation resulting in higher molecular weight. This produces a "hardening" of the elastomer. It is caused by cross-linking, branching, cyclization, and further polymerization.

Chemical alteration of the molecule by introduction of new chemical groups. The alteration accompanies the foregoing two phenomena but can also be entirely different in its end result.

Whether the oxidative changes result in a softening or hardening of the composition depends on many factors, some external to the material and some internal. These factors can be listed as follows.

External Factors	Internal Factors
1. Oxygen generally considered responsible for most all aging phenomena	1. Type of rubber
2. Heat accelerates the action of oxygen and at higher temperatures produces degradation by itself	2. Degree and type of vulcanization
3. Pro-oxidants - sulfur, metal contaminants	3. Accelerators used and their residues
4. Ozone highly active form of oxygen, producing severe degradation in extremely low concentrations	4. Type of compounding ingredients
5. Fatigue	5. Processing factors
6. Light and weathering	6. Protective agents
7. Radiation	7. Auto inhibition

Table VI lists the properties of some typical rubber compounds affecting their choice as a seal material.

2. PLASTICS

The physical and mechanical properties of plastic materials are well defined. Terminology applicable to metallic material studies is applicable to plastics with the exception of the fact that elastic deformation occurs during such a small region of loading that it may be termed nonexistent. The following tables (VII through IX) are of physical, mechanical, and chemical resistance properties of some typical plastic materials.

Table VI

Properties and Applications of Some Typical Rubber Compounds (Ref. 7)

	Sp. Gr. of Base Elastomers	Durometer Hardness Range (Shore A)	T.S. (psi at Room Temp)	Elongation (percent at Room Temp.)	Max. Svc. Temp. °F	Min. Svc. Temp. °F	Tear Resistance	Abrasion Resistance
Acrylic	1.10	40-100	500-2200	100-400	300-400	-20 0 Poor	Fair	Good
Poly isobutylene	0.92	30-100	3000	500-700	250	-70 -60 Very good	Very good	Good
Urethane	0.85	62-95	8000	700	250	-90 -40 Very good	Excellent	Superior
Ethylene Propylene (EPR)	0.85	30-100	3000	300	300	-50 -40 Very good	Good	Excellent
Fluoro-elastomers	1.4 1.95	60-90	2400	350	600	-40 -20 Fair	Fair	Good
Chloro-sulfonated polyethylene	1.10	50-95	2800	500	250	-68 0 Good	Good	Excellent
Natural rubber	0.93	20-100	4000	700	212	-65 -40 Very good	Very good	Excellent
Neoprene	1.23	20-90	4000	700	212	-65 -40 Good	Good	Excellent
Polybuta-diene	1.93	30-100	3000	700	212	-80 -50 Very good	Very good	Excellent
Polyiso prene	0.94	20-100	4000	750	212	-50 -30 Very good	Very good	Excellent
Polysulfide	1.34	20-80	1250	400	212	-60 -45 Very good	Good	Poor
Styrene butadiene (SBR)	0.94	40-100	3500	700	225	-40 -30 Good	Good	Excellent
Silicone	0.98	20-95	1500	800	550	Superior	Poor	Poor

SUPPLEMENTARY

INFORMATION

ERRATA FOR AFFDL-TR-65-88, PART II

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